

# Monitoring Forest Carbon in Sierra Nevada and North Coast Forests with Field Inventories, LIDAR, and QuickBird

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Tahoe National Forest, California (photo ©2005 P. Gonzalez)

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## Research Partners

California Department  
of Parks and Recreation  
Carnegie Institution of Washington  
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The Conservation Fund  
The Nature Conservancy  
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The Nature  
Conservancy



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Colorado  
State  
University

THE CONSERVATION FUND



## **Mission**

**The mission of The Nature Conservancy is to preserve the plants, animals, and natural communities that represent the diversity of life on Earth by protecting the lands and waters they need to survive.**

## **2015 Goal**

**By 2015, The Nature Conservancy will work with others to ensure the effective conservation of places that represent at least 10% of every major habitat type on Earth.**

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## Presentation Outline

1. Forest Carbon Balance and Densities
2. Research Areas
  - a. North Yuba carbon
  - b. Garcia-Mailliard carbon
3. Methods
  1. Forest inventories
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# Monitoring Forest Carbon in Sierra Nevada and North Coast Forests with Field Inventories, LIDAR, and QuickBird Satellite Images

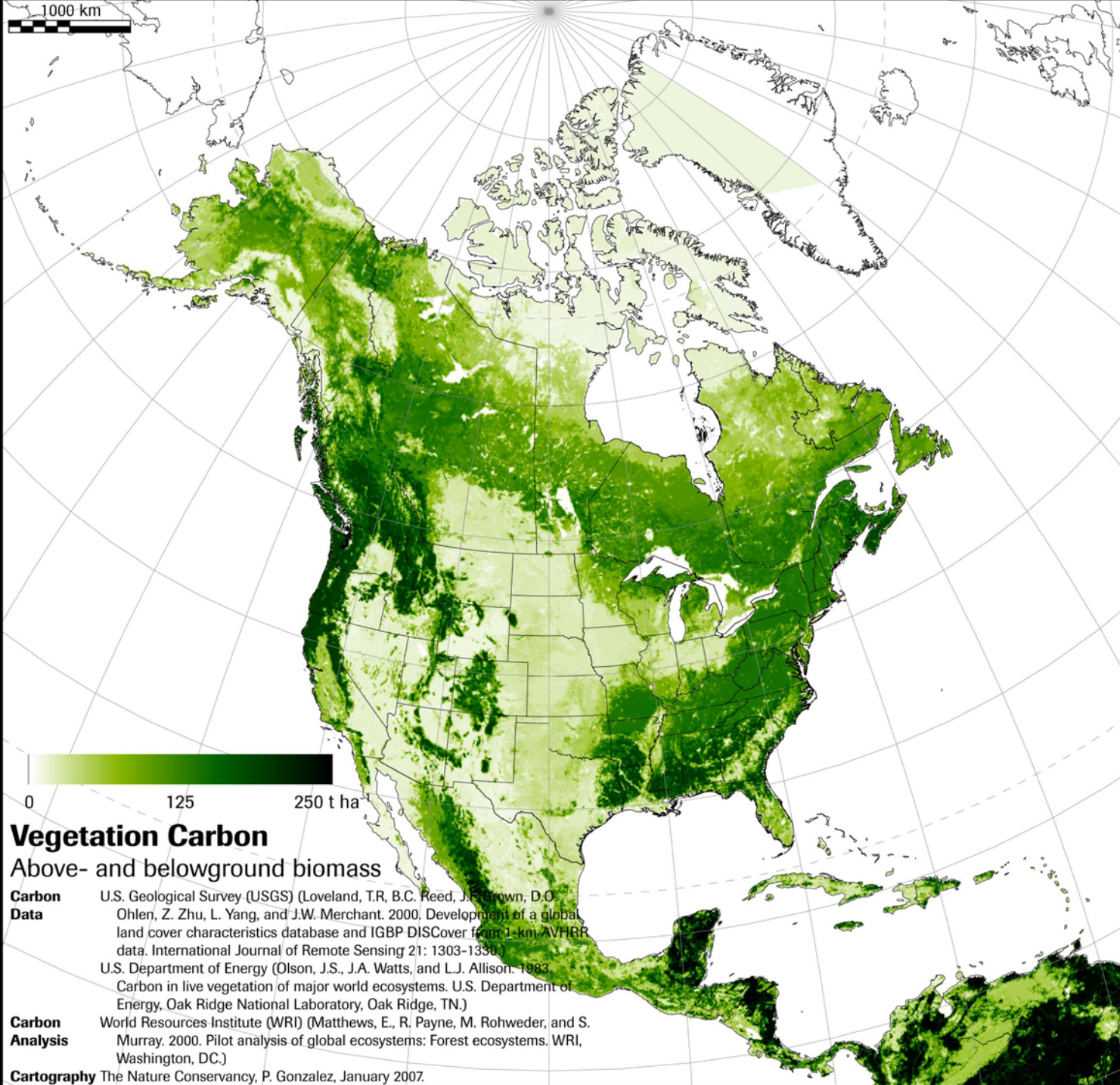
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# Global Carbon Budget 2000-2005

<b>Fossil fuel emissions</b>	<b><math>+7.2 \pm 0.3</math> billion t y<sup>-1</sup></b>
<b>Deforestation</b>	<b><math>+1.6 \pm 1.1</math> billion t y<sup>-1</sup></b>
<b>Gross uptake by vegetation and soils</b>	<b><math>-2.6 \pm 1.7</math> billion t y<sup>-1</sup></b>
<b>Net Uptake by oceans</b>	<b><math>-2.2 \pm 0.5</math> billion t y<sup>-1</sup></b>
<hr/>	
<b>Accumulation in the atmosphere</b>	<b><math>+4.1 \pm 0.1</math> billion t y<sup>-1</sup></b>

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, UK.





## High-Carbon Forests

### Coast Redwoods, California

**1600-2800 t ha<sup>-1</sup>**

**highest carbon density in the world  
(Busing and Fujimori 2005)**

### Sierra Nevada conifers, California

**160 ± 3 t ha<sup>-1</sup>**

**(Lefsky et al. manuscript in  
preparation from this research)**

### Amazon rainforest

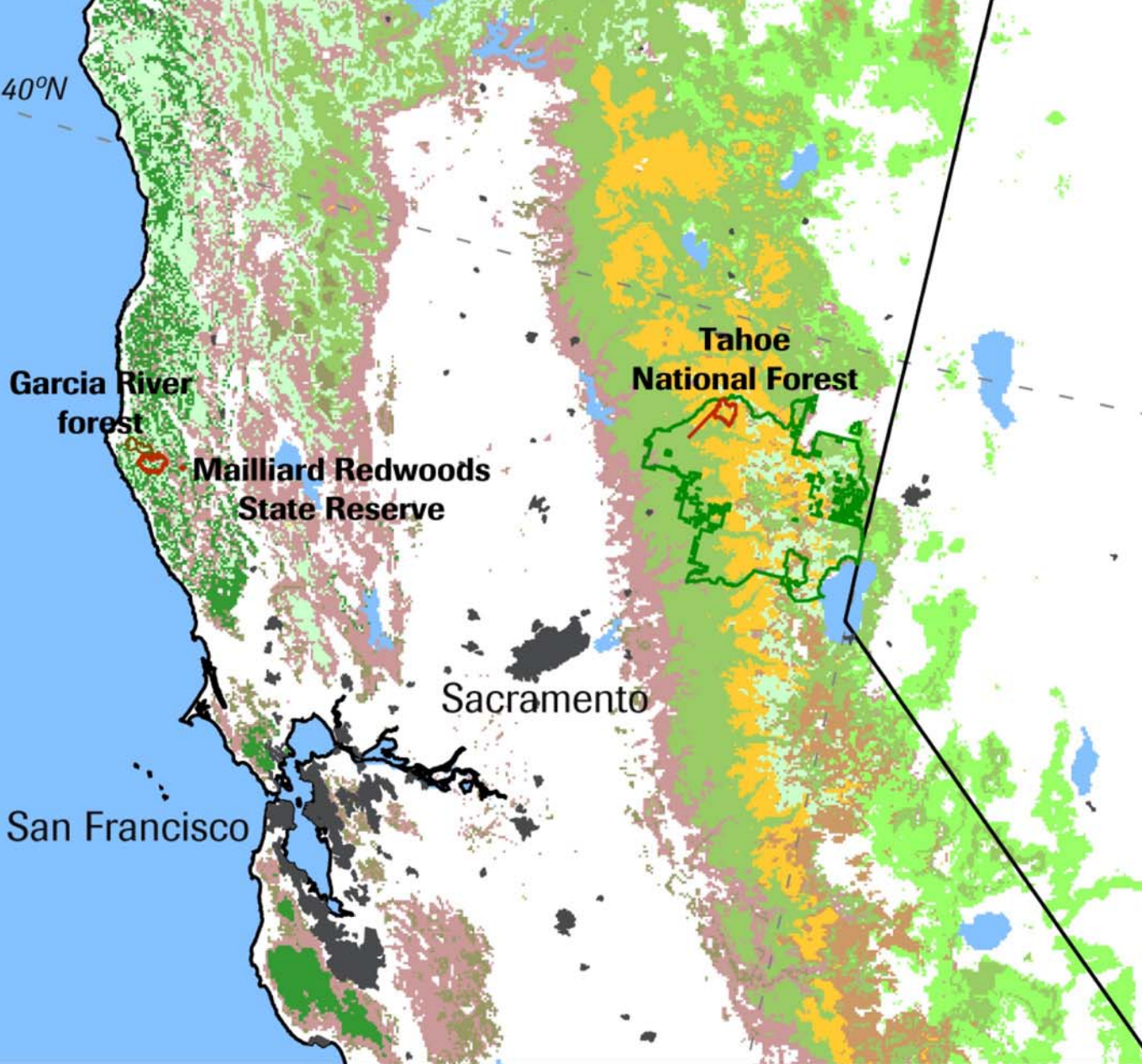
**170 ± 9 t ha<sup>-1</sup>**

**(Baker et al. 2004)**

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## California Climate Change Research Sites

### Forest Cover

U.S. Geological Survey (USGS) (Zhu, Z. and D.L. Evans. 1994. U.S. forest types and predicted percent forest cover from AVHRR data. Photogrammetric Engineering and Remote Sensing 60: 525-531.)

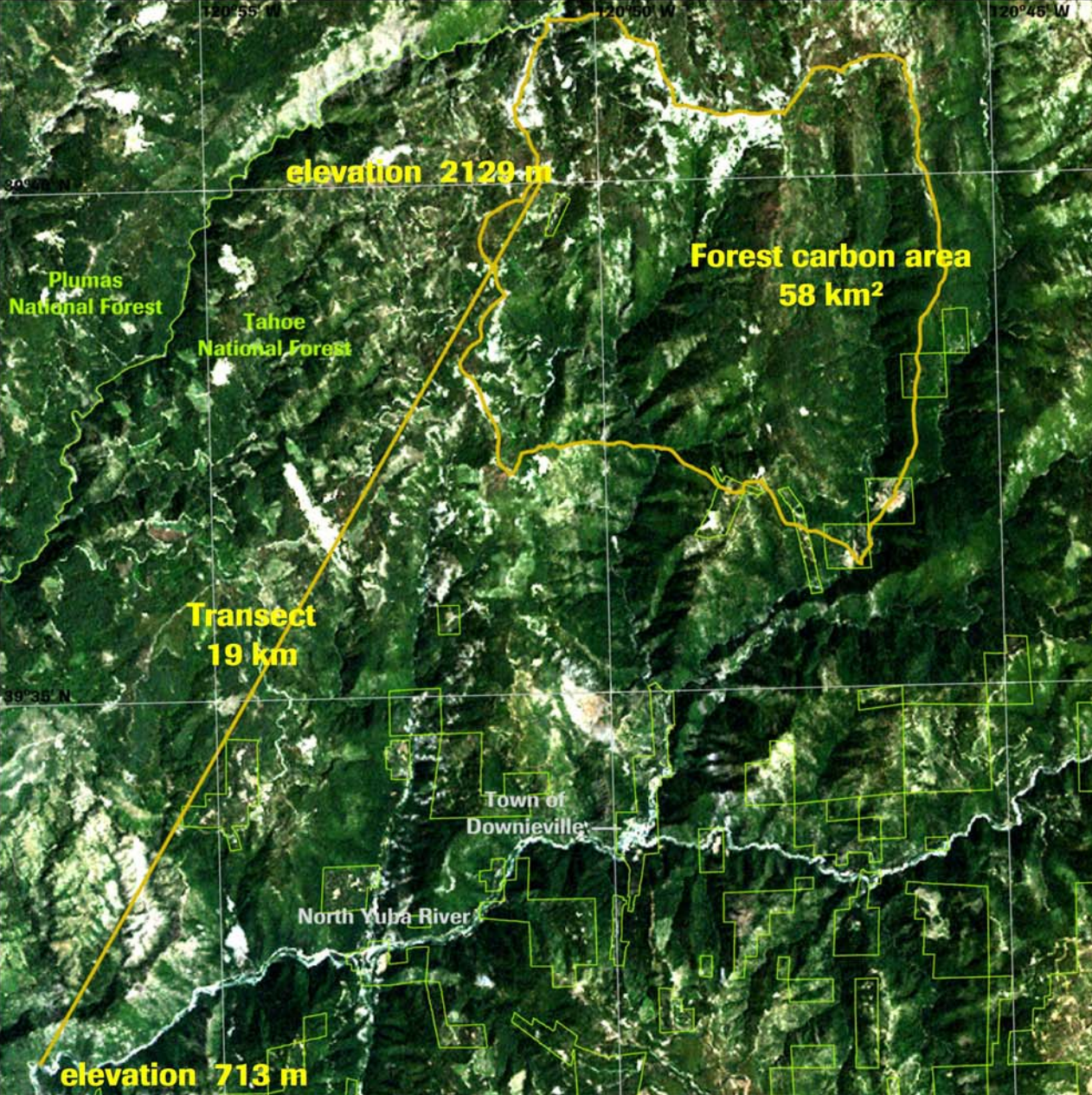
U.S. Department of Agriculture, Forest Service (USDA FS) (Smith, W.B., J.S. Vissage, D.R. Darr, and R.M. Sheffield. 2001. Forest Resources of the United States, 1997. USDA FS, St. Paul, MN.)

### Urban Areas

U.S. Geological Survey, 2001.

### Cartography

The Nature Conservancy, P. Gonzalez, May 2005.  
U.S. Geological Survey, J. Hutchinson, August 2000.



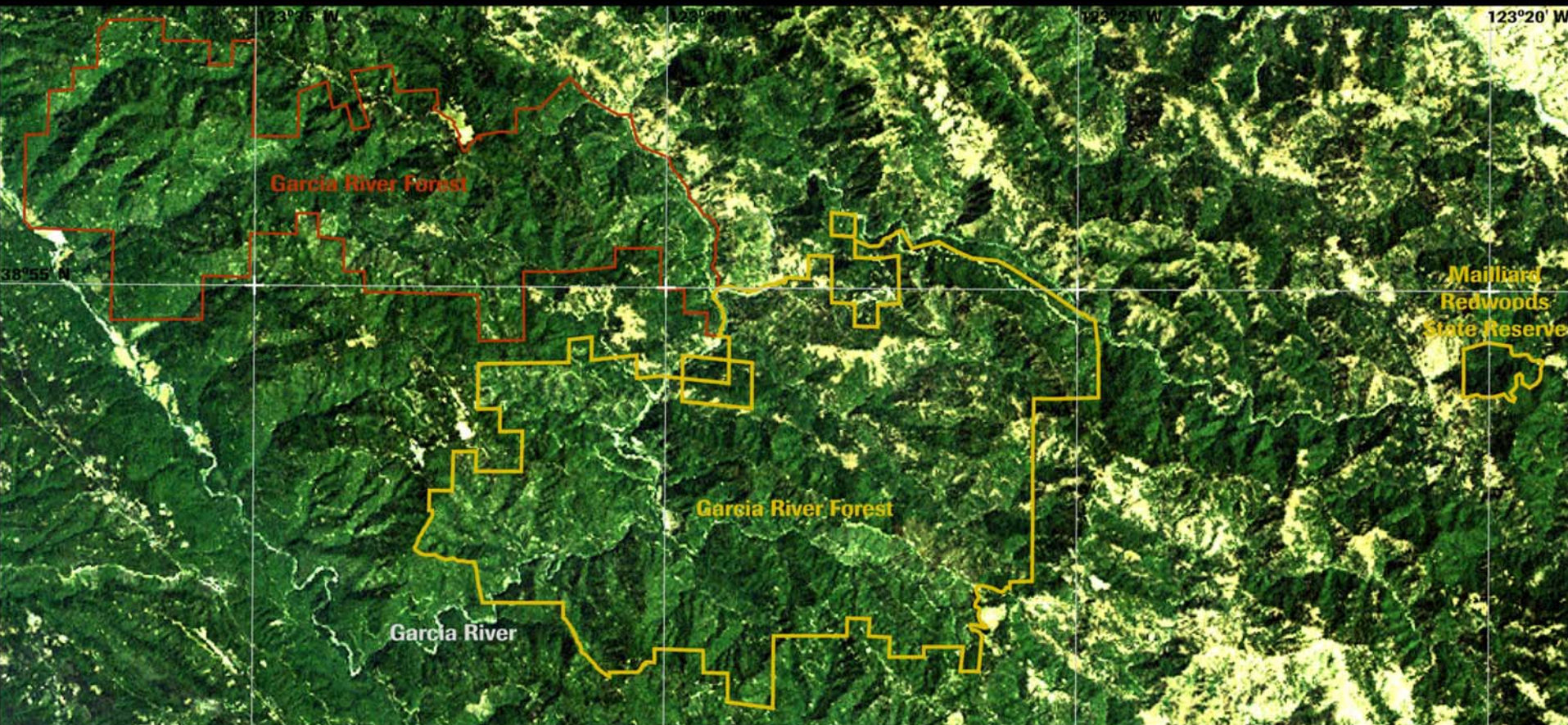
## North Yuba River climate change research areas

image USGS Landsat, July 18, 2000  
data USDA FS  
cartography P. Gonzalez



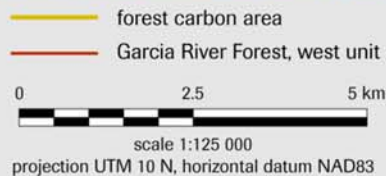
# Garcia River Forest

## Mailliard Redwoods State Reserve, California



### Forest Carbon Research

The Nature Conservancy  
The Conservation Fund  
California Department of Parks and Recreation  
U.S. Department of Energy  
Carnegie Institution of Washington  
Colorado State University  
Stanford University  
University of California, Berkeley



remote sensing: U.S. Geological Survey, Landsat, August 17, 2000  
cartography: The Nature Conservancy, P. Gonzalez, May 2005





Maillards Redwoods State Reserve, California (photo ©2006 P. Gonzalez)



## **Garcia River Forest Project**

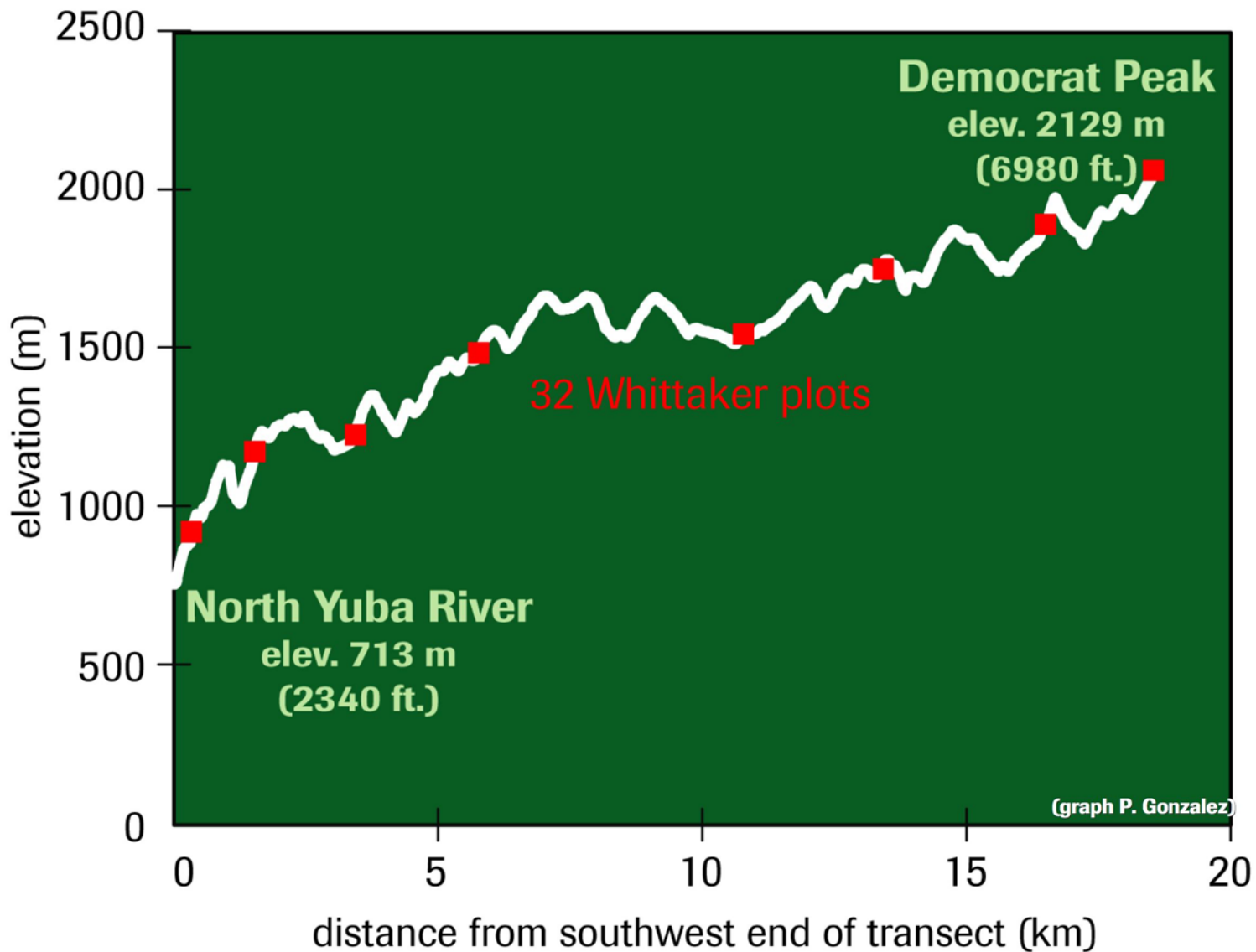
- Forest management project registered under the California Climate Action Registry
- Registry Forestry Protocols employed in project design
- 9700 ha of forest conservation, reforestation, and harvesting

## **Forest Conservation and Reforestation Ecosystem Services**

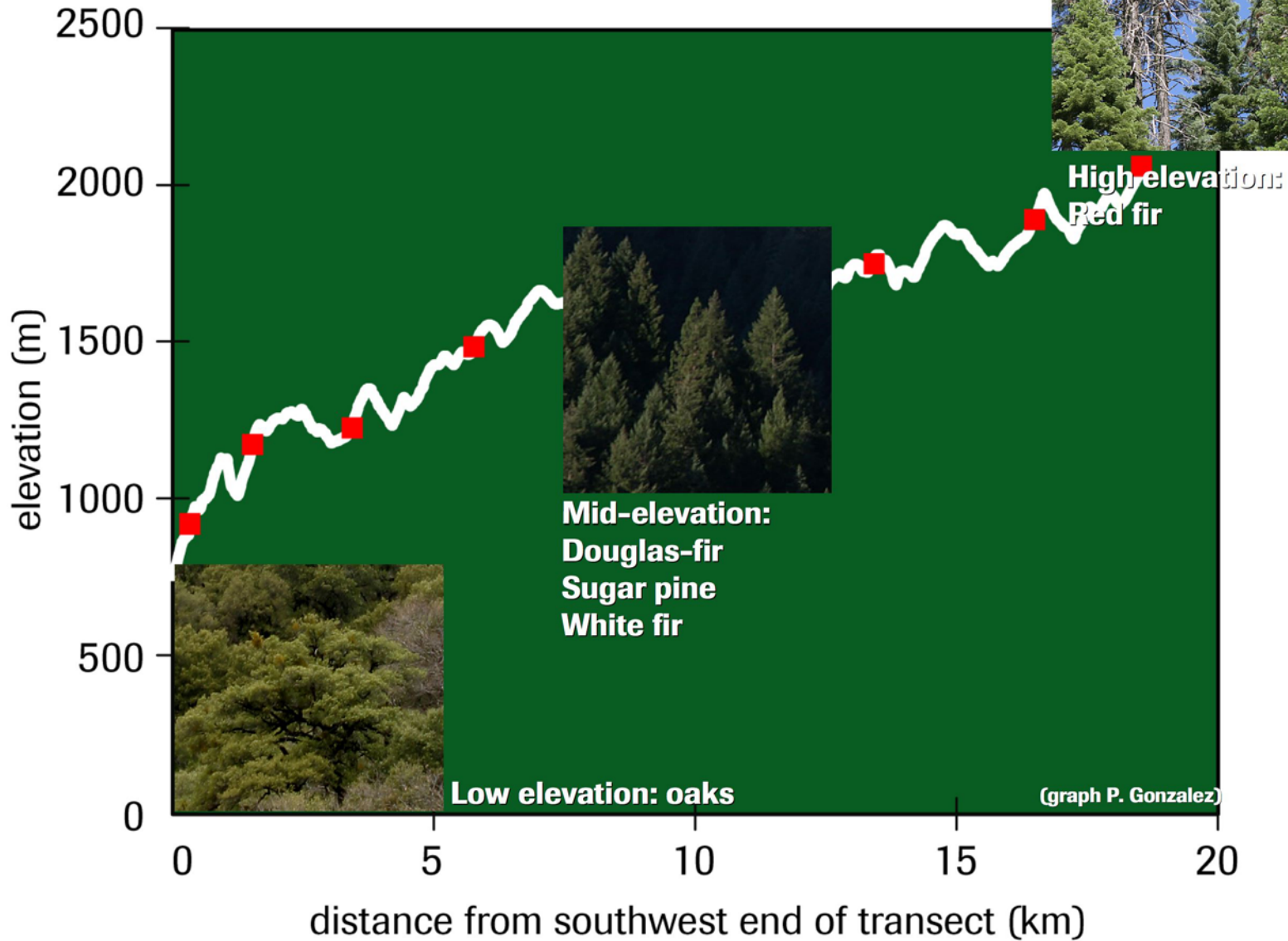
- Biodiversity conservation
- Carbon sequestration
- Ecosystem resilience to climate change
- Forest products
- Watershed protection
- Agricultural soil conservation
- Bee pollination
- Scenic values

Louis Blumberg in Garcia River forest (photo ©2007 P. Gonzalez)

# Climate Change Transect, Tahoe National Forest



# Climate Change Transect, Tahoe National



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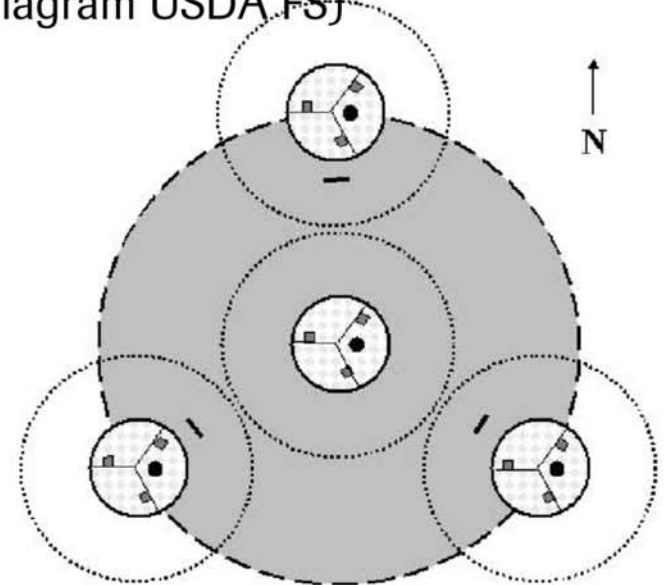
# Permanent Forest Inventory Plots

- Modified USDA Forest Service Forest Inventory and Analysis (FIA) design
- Grid of 1.5 km for systematic sample (North Yuba); stratified random sample of 5 diameter classes (Garcia-Mailliard)
- Aboveground live and dead trees, shrubs, coarse woody debris, litter
- Tree species, heights, diameters, crowns
- Fire fuels, 1-, 10-, 1000-hour
- Species-specific allometric equations for biomass
- Derivation of equation of biomass vs. crown diameter
- Two-step Monte Carlo analysis of measurement, sampling, and statistical uncertainty



Crew leader Garrett Meigs measuring tree (photo ©2005 P. Gonzalez)

## USDA Forest Service Forest Inventory and Analysis plot (diagram USDA FS)

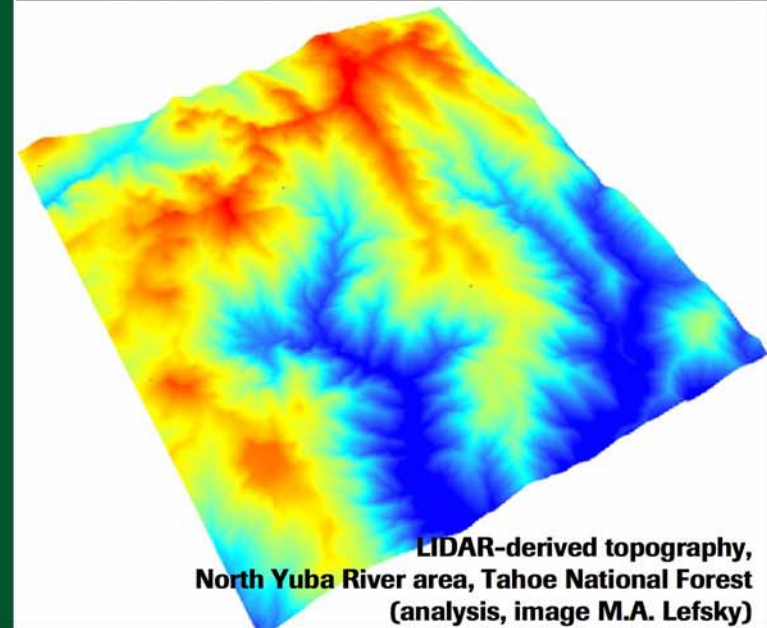
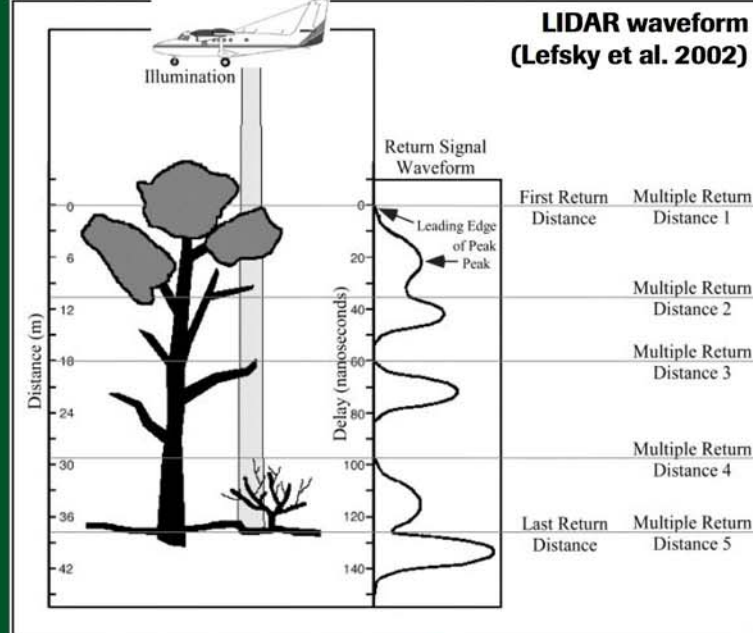


○ Subplot	24.0 ft ( 7.32 m) radius
● Microplot	6.8 ft ( 2.07 m) radius
○ Annular plot	58.9 ft (17.95 m) radius
○ Lichens plot	120.0 ft (36.60 m) radius
■ Vegetation plot	1.0 m <sup>2</sup> area
— Soil Sampling	(point sample)
— Down Woody Debris	24.0 ft ( 7.32 m) transects

# Light Detection and Ranging (LIDAR)

- Airplane altitude 800 m above ground
- Laser frequency 38 Hz
- Pulse spacing 1 m
- Vertical accuracy (RMSE)  $\pm 15$  cm
- Horizontal accuracy (RMSE)  $\pm 50$  cm
- Swath width 580 m
- Employed progressive morphological filter to determine ground elevation at 2 m horizontal resolution
- Used LIDAR first return to determine canopy height
- Derived biomass equation from stepwise multiple regression of biomass vs. LIDAR-derived height metrics at 25 m horizontal resolution for canopy of  $h > 2.8$  m
- Conducted two-step Monte Carlo analysis to quantify measurement, sampling, and statistical error

**LIDAR waveform**  
(Lefsky et al. 2002)

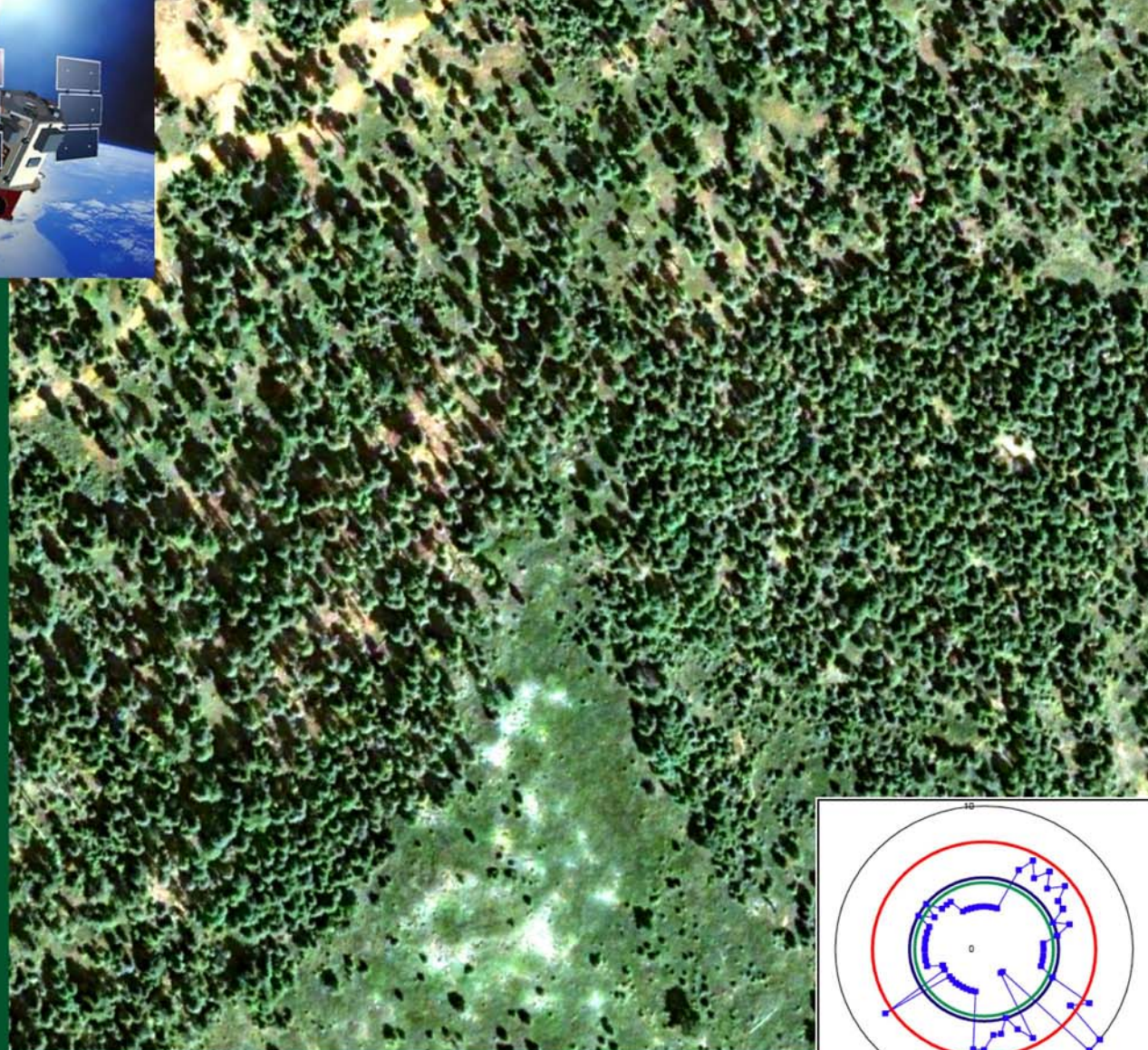


**LIDAR-derived topography,**  
North Yuba River area, Tahoe National Forest  
(analysis, image M.A. Lefsky)

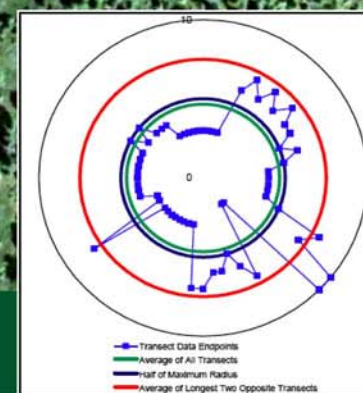
# QuickBird High-Resolution Satellite



- Orbital altitude 450 km
- Panchromatic resolution 60 cm
- Multi-spectral resolution 2.4 m
- Sensor and radiometric correction, orthorectification
- Horizontal accuracy 6.2 m RMSE
- Calculated Normalized Difference Vegetation Index (NDVI) to identify forest area
- Detected crowns using local maxima and minima filtering
- Created spatial data layer of crown perimeters and crown diameters
- Used forest inventory equation of biomass vs. crown diameter to calculate biomass at 25 m resolution
- Conducted two-step Monte Carlo analysis to quantify measurement, sampling, and statistical error



Top: QuickBird Satellite (DigitalGlobe, Inc.)  
Bottom: QuickBird image, part of Tahoe National Forest, August 2, 2005  
Right: Crown detection (G.P. Asner and M. Palace)



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## Forest Inventories North Yuba Forest Carbon Area

- Measured and tagged 1526 trees of diameter  $>19.5$  cm at  $h = 1.37$  m
- Measured 5590 other live and dead trees of all diameters
- Eleven tree species, *Abies concolor* (white fir) dominant
- Average density  $830 \pm 700$  trees  $\text{ha}^{-1}$
- Mean diameter  $37 \pm 15$  cm
- Aboveground biomass  $520 - 1100$  t  $\text{ha}^{-1}$
- Aboveground vegetation carbon (live trees, dead trees, shrubs, coarse woody debris, litter)  $240 - 500$  t  $\text{ha}^{-1}$
- Fraction of aboveground carbon in live trees 0.70-0.80

*Pseudotsuga menziesii* (Douglas-fir), Tahoe National Forest, California (photo ©2005 P. Gonzalez)

# North Yuba Forest Carbon Area Species Composition

		fraction	
		trees	biomass
<i>Abies concolor</i>	white fir	0.46	0.50
<i>Abies magnifica</i>	red fir	0.14	0.20
<i>Acer macrophyllum</i>	bigleaf maple	0.01	<0.01
<i>Calocedrus decurrens</i>	incense cedar	0.03	0.01
<i>Pinus jeffreyi</i>	jeffrey pine	<0.01	<0.01
<i>Pinus ponderosa</i>	ponderosa pine	0.01	0.02
<i>Pinus lambertiana</i>	sugar pine	0.09	0.09
<i>Pinus monticola</i>	western white pine	0.01	0.01
<i>Pseudotsuga menziesii</i>	Douglas-fir	0.10	0.13
<i>Quercus kelloggii</i>	California black oak	0.09	0.03
<i>Quercus chrysolepis</i>	canyon live oak	0.06	0.01

*Calocedrus decurrens*, *Pseudotsuga menziesii*, Tahoe National Forest, California (photo ©2005 P. Gonzalez)

# North Yuba Forest Carbon Area Aboveground Biomass

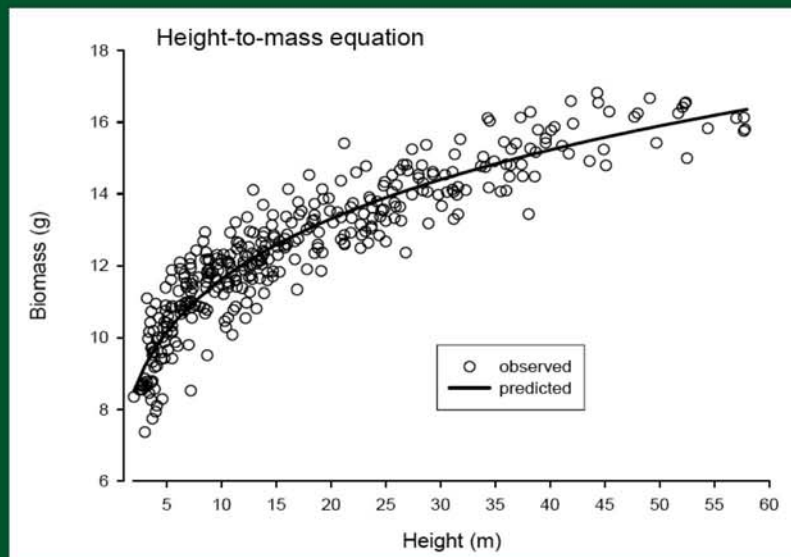
	hardwood/ Douglas-fir	mixed conifer	red fir
<b>plots</b>	<b>6</b>	<b>30</b>	<b>3</b>
<b>samples</b>	<b>24</b>	<b>108</b>	<b>12</b>

## Biomass (t ha<sup>-1</sup>) (mean ± s.d.)

<b>live trees</b>	<b>420 ± 260</b>	<b>380 ± 200</b>	<b>750 ± 140</b>
<b>dead trees</b>	<b>22 ± 22</b>	<b>40 ± 40</b>	<b>120 ± 63</b>
<b>coarse woody debris</b>	<b>3 ± 4</b>	<b>4 ± 5</b>	<b>18 ± 22</b>
<b>shrubs</b>	<b>1</b>	<b>2</b>	<b>0</b>
<b>litter</b>	<b>78 ± 54</b>	<b>100 ± 44</b>	<b>170 ± 30</b>
<b>Total aboveground</b>	<b>520 ± 640</b>	<b>530 ± 390</b>	<b>1100 ± 480</b>

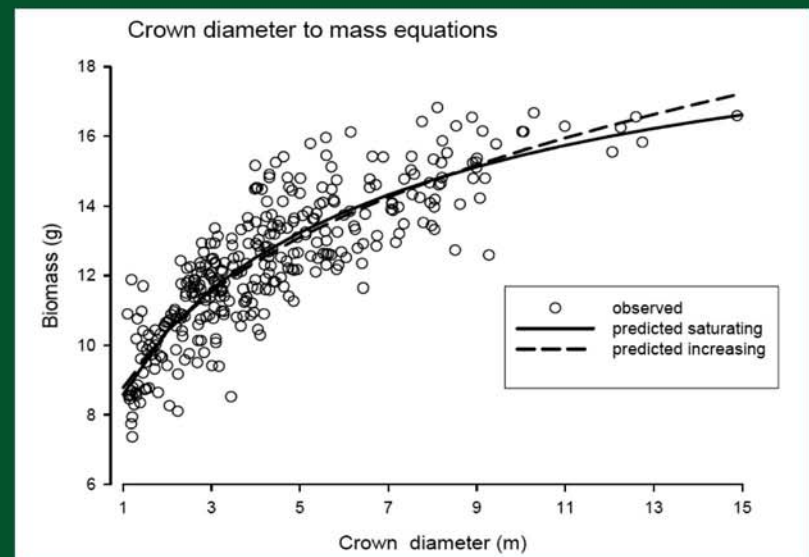
# North Yuba Forest Carbon Area

Allometric equations derived using likelihood analysis and Akaike's Information Criterion  
(analysis, graphs J.J. Battles, K. Waring; manuscript in preparation)



$$\ln(\text{biomass}) = 7.4312 * (\text{height}^{0.1943})$$

$n = 362, r^2 = 0.86$



$$\ln(\text{biomass}) = 18.613 * ((1 - e^{-0.0757 * \text{diameter}})^{0.2963})$$

$n = 331, r^2 = 0.73$

## Forest Inventories Garcia-Mailliard Forest Carbon Area

- Measured and tagged 3306 trees of diameter  $>19.5$  cm at  $h = 1.37$  m
- Eleven tree species, *Sequoia sempervirens* (coast redwood) dominant in Mailliard, *Lithocarpus densiflorus* (tanoak) dominant in Garcia
- Average density  $3600 \pm 2100$  trees  $\text{ha}^{-1}$  (Garcia),  $1900 \pm 1900$  trees  $\text{ha}^{-1}$  (Mailliard)
- Mean diameter =  $38 \pm 25$  cm
- Aboveground biomass  $220 \pm 90$  t  $\text{ha}^{-1}$  (Garcia),  $700 \pm 300$  t  $\text{ha}^{-1}$  (Mailliard)
- Aboveground carbon  $100 \pm 40$  t  $\text{ha}^{-1}$  (Garcia),  $320 \pm 140$  t  $\text{ha}^{-1}$  (Mailliard)

East of Garcia and Mailliard, California (photo ©2005 P. Gonzalez)

## Garcia-Mailliard Forest Carbon Area Species Composition

			fraction		
		Garcia trees	Garcia biomass	Mailliard trees	Mailliard biomass
<i>Acer glabrum</i>	bigleaf maple			0.01	0.00
<i>Arbutus menziessii</i>	Pacific madrone	0.05	0.06	0.06	0.03
<i>Lithocarpus decurrens</i>	tanoak	0.27	0.47	0.50	0.22
<i>Pinus lambertiana</i>	sugar pine	0.03	0.02		
<i>Pseudotsuga menziesii</i>	Douglas-fir	0.28	0.29	0.16	0.38
<i>Quercus agrifolia</i>	coast live oak	0.01	0.01		
<i>Quercus chrysolepis</i>	canyon live oak	0.03	0.02	0.01	0.00
<i>Quercus kelloggii</i>	California black oak	0.02	0.02		
<i>Sequoia sempervirens</i>	coast redwood	0.28	0.09	0.24	0.36
<i>Torreya californica</i>	California nutmeg	0.01	0.00	0.02	0.00

# Garcia-Mailliard Forest Carbon Area Aboveground Biomass

	Garcia	Mailliard	Total
<b>plots</b>	<b>112</b>	<b>48</b>	<b>160</b>
<b>samples</b>	<b>28</b>	<b>12</b>	<b>40</b>
<b>Biomass (t ha<sup>-1</sup>) (mean ± s.d.)</b>			
<b>live trees</b>	<b>210 ± 75</b>	<b>670 ± 270</b>	<b>340 ± 130</b>
<b>dead trees</b>	<b>7 ± 11</b>	<b>18 ± 25</b>	<b>10 ± 16</b>
<b>coarse woody debris</b>	<b>6 ± 7</b>	<b>6 ± 10</b>	<b>6 ± 8</b>
<b>shrubs</b>	<b>1</b>	<b>0</b>	<b>&lt; 1</b>
<b>Total aboveground</b>	<b>220 ± 93</b>	<b>690 ± 310</b>	<b>360 ± 160</b>

# Garcia-Mailliard Forest Carbon Area

Allometric equations derived using likelihood analysis and Akaike's Information Criterion  
(analysis J.J. Battles, K. Waring; manuscript in preparation)

Eqn 7 (GRF):  $\text{natural log (biomass)} = 8.573 * \text{cdiam}^{0.2078}, R^2 = 0.55$

Eqn 8 (MRSR):  $\text{natural log (biomass)} = 8.82 * \text{cdiam}^{0.2217}, R^2 = 0.59$

Table 11. Results from GRF: competing models prediction natural log tree biomass in grams (y) from crown diameter in meters (x). N = 261 (one outlier removed).

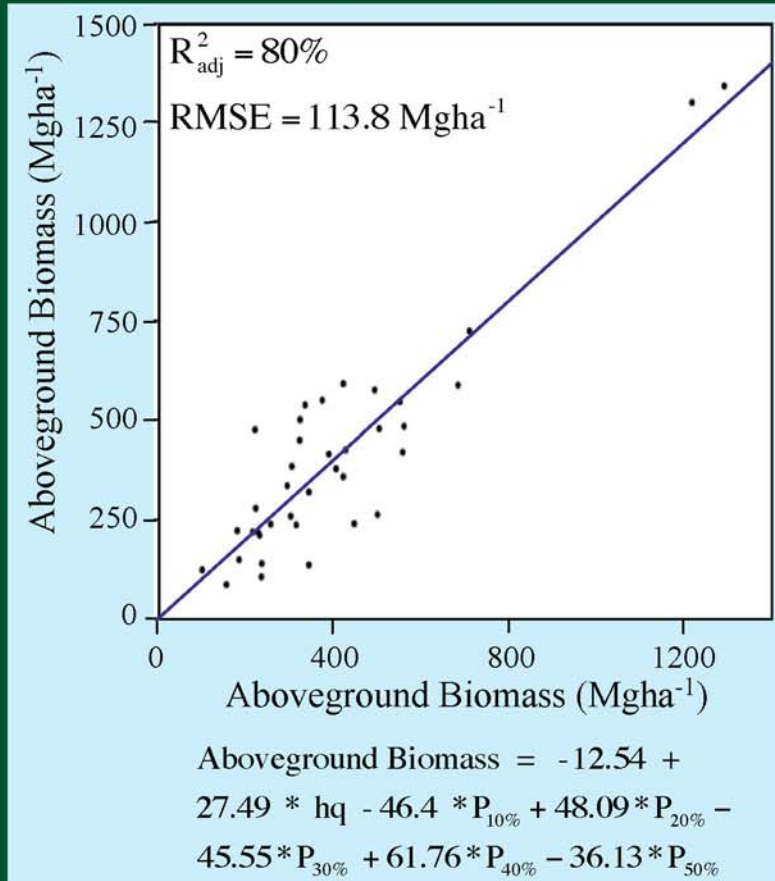
Model	Name	Negative Log Likelihood	AIC
<b>Increasing functions</b>			
$\text{Log}(y)=a+bx$	Linear	-316.79	639.59
$\text{Log}(y)=a*x^b$	Power	-312.88	631.75
<b>Saturating functions</b>			
$\text{Log}(y) = a*x/(b+x)$	Michaelis-Menton	-317.84	641.69
$\text{Log}(y)=a*((1-\exp(b*x))^c)$	Chapman Richards	Non convergence	

Table 12. Results from MRSR: competing models prediction natural log tree biomass in grams (y) from crown diameter in meters (x). N = 102 (one outlier removed).

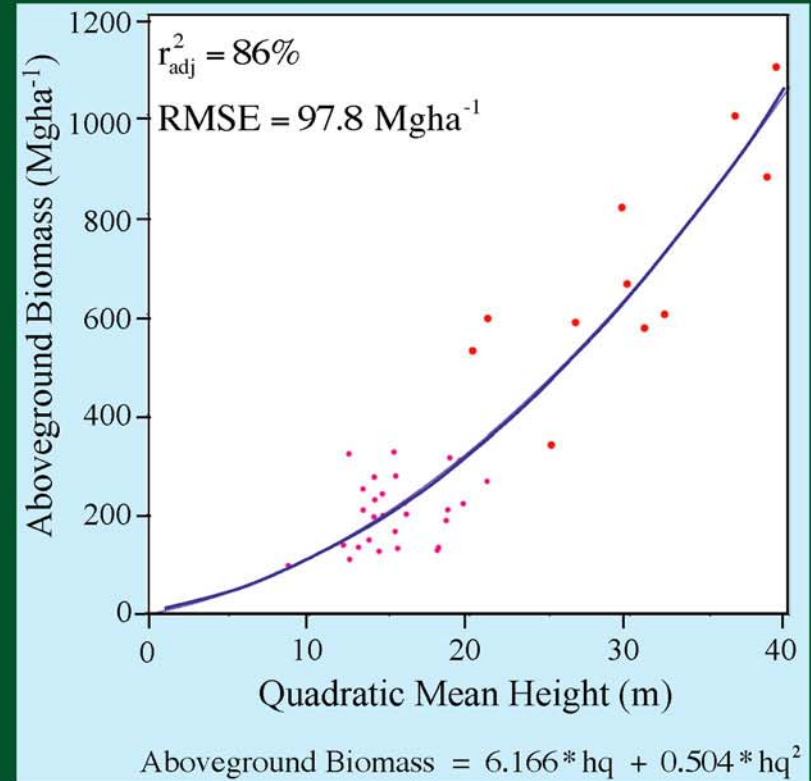
Model	Name	Negative Log Likelihood	AIC
<b>Increasing functions</b>			
$\text{Log}(y)=a+bx$	Linear	-152.95	311.90
$\text{Log}(y)=a*x^b$	Power	-149.41	304.83
<b>Saturating functions</b>			
$\text{Log}(y) = a*x/(b+x)$	Michaelis-Menton	-153.75	313.49
$\text{Log}(y)=a*((1-\exp(b*x))^c)$	Chapman Richards	-149.96	307.92

# LIDAR biomass regression equations derived by least squares multiple regression (analysis, graphs M.A. Lefsky; manuscript in preparation)

North Yuba



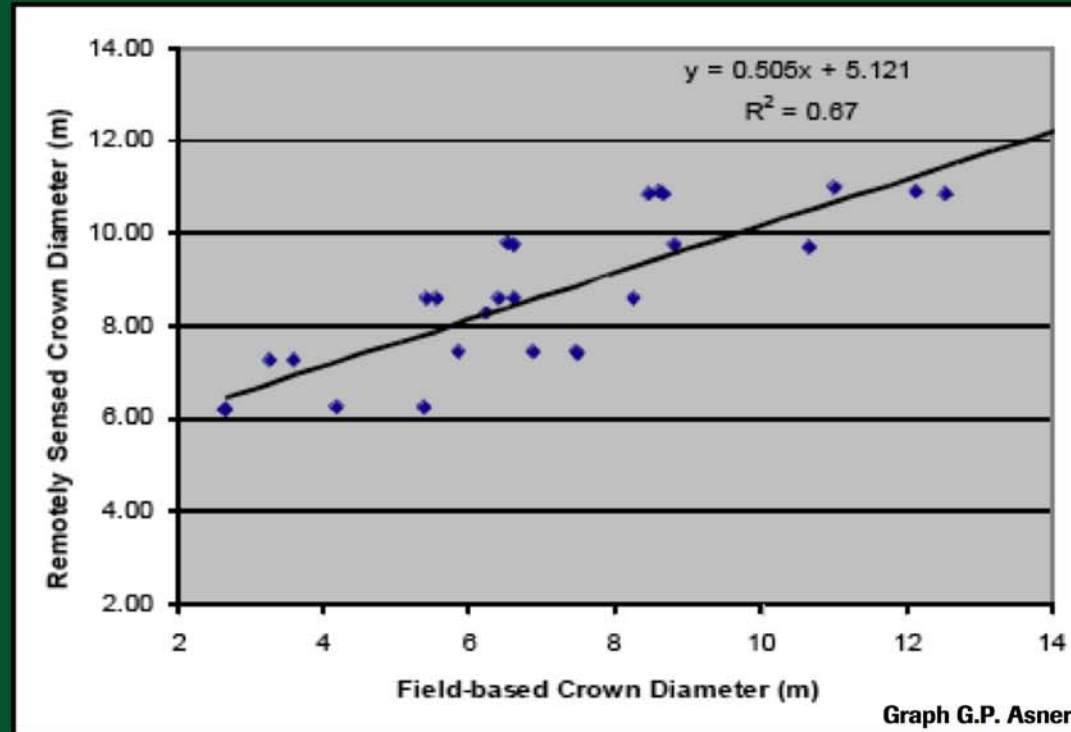
Garcia-Mailliard



# QuickBird

## North Yuba Forest Carbon Area Crown Diameter

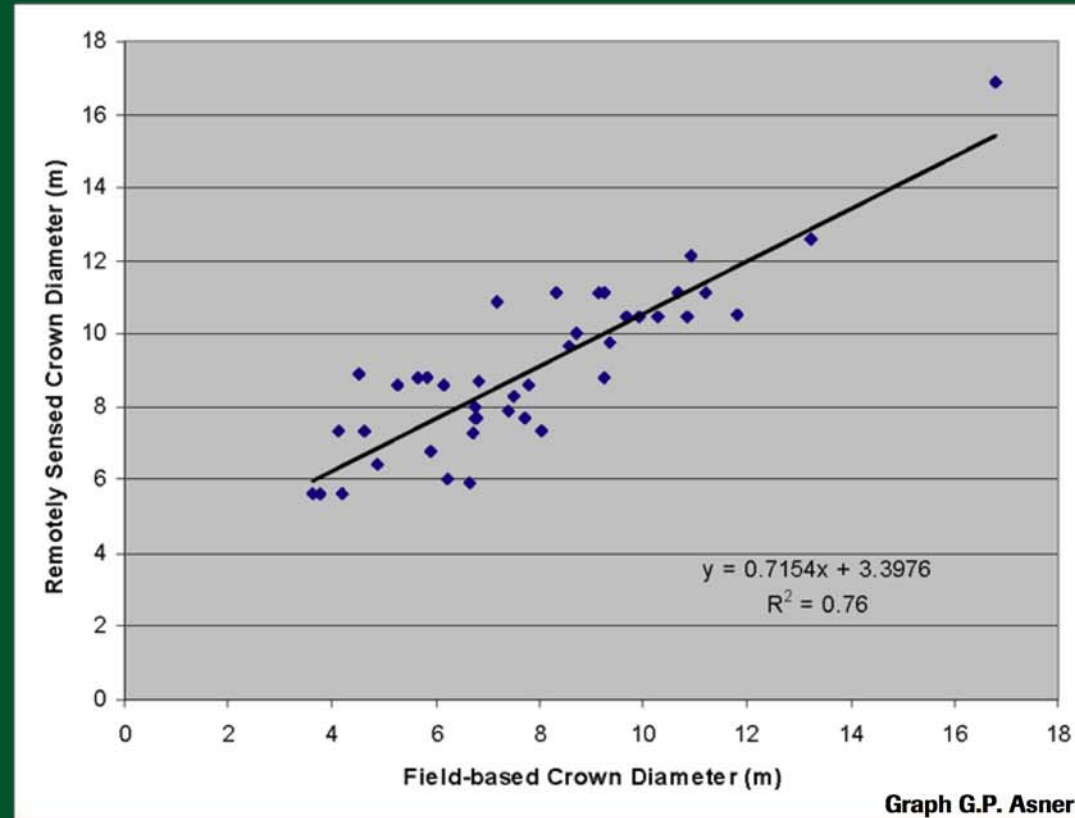
- Detection and measurement of 681 000 tree crowns
- Difficulties in crown delineation due to shadows
- Minimum crown diameter = 2.4 m
- Correlation of QuickBird-derived crown diameter and field-measured crown diameters
- Two-step Monte Carlo analysis similar to LIDAR error propagation analysis
- Estimated average biomass =  $240 \text{ t ha}^{-1} \pm 100 \text{ t ha}^{-1}$



# LIDAR

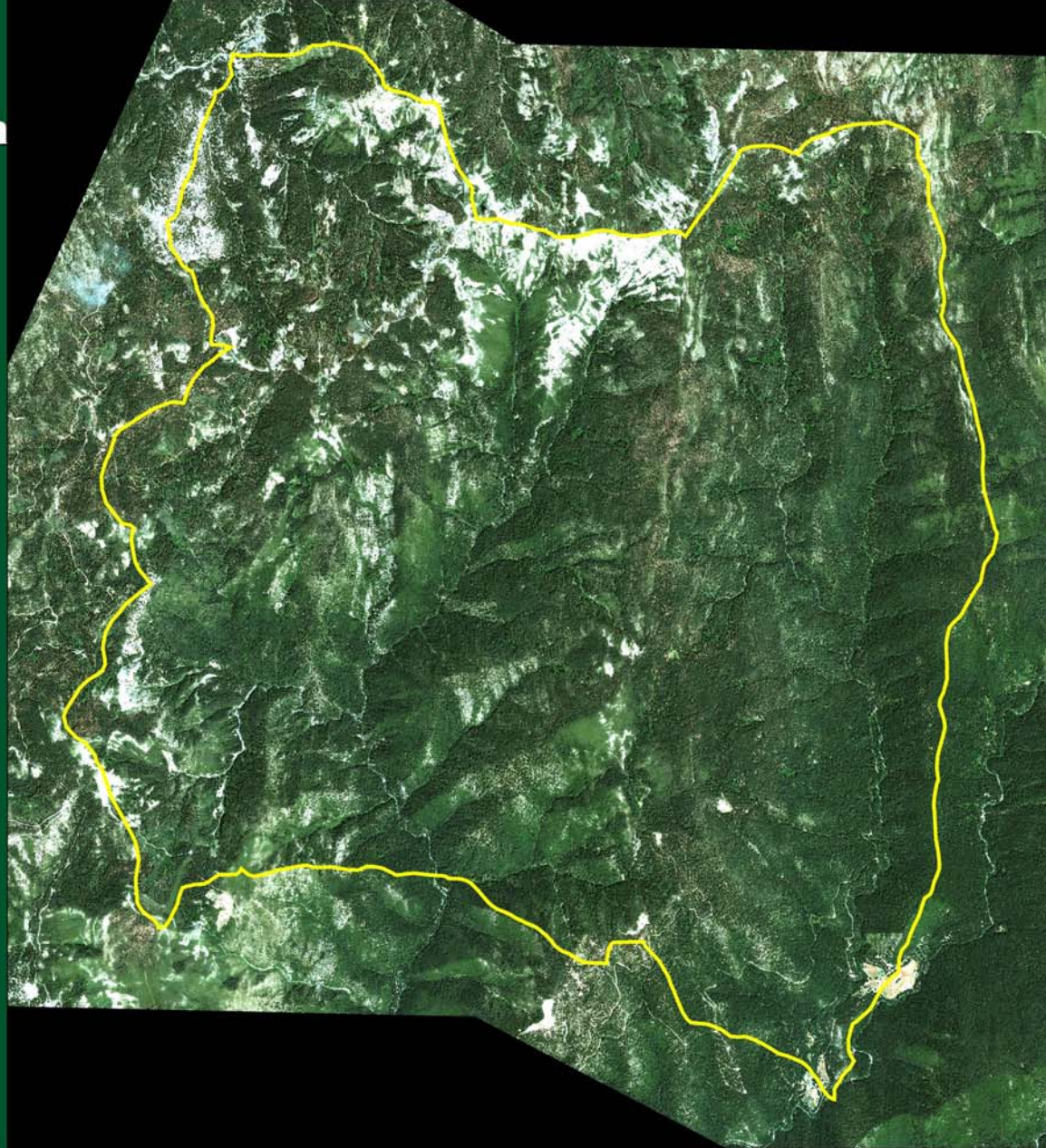
## North Yuba Forest Carbon Area Crown Diameter

- Detection and measurement of 1.7 million tree crowns
- Difficulties in crown delineation due to shadows and bright spots
- Overestimation of crown diameter for actual diameters  $< 10$  m
- Underestimation of crown diameter for actual diameters  $> 11$  m
- Two-step Monte Carlo analysis similar to LIDAR error propagation
- Estimated Garcia biomass =  $230 \text{ t ha}^{-1} \pm 120 \text{ t ha}^{-1}$
- Estimated Mailliard biomass =  $260 \text{ t ha}^{-1} \pm 160 \text{ t ha}^{-1}$



# QuickBird North Yuba Forest Carbon Area Real Color

▪ August 2, 2005

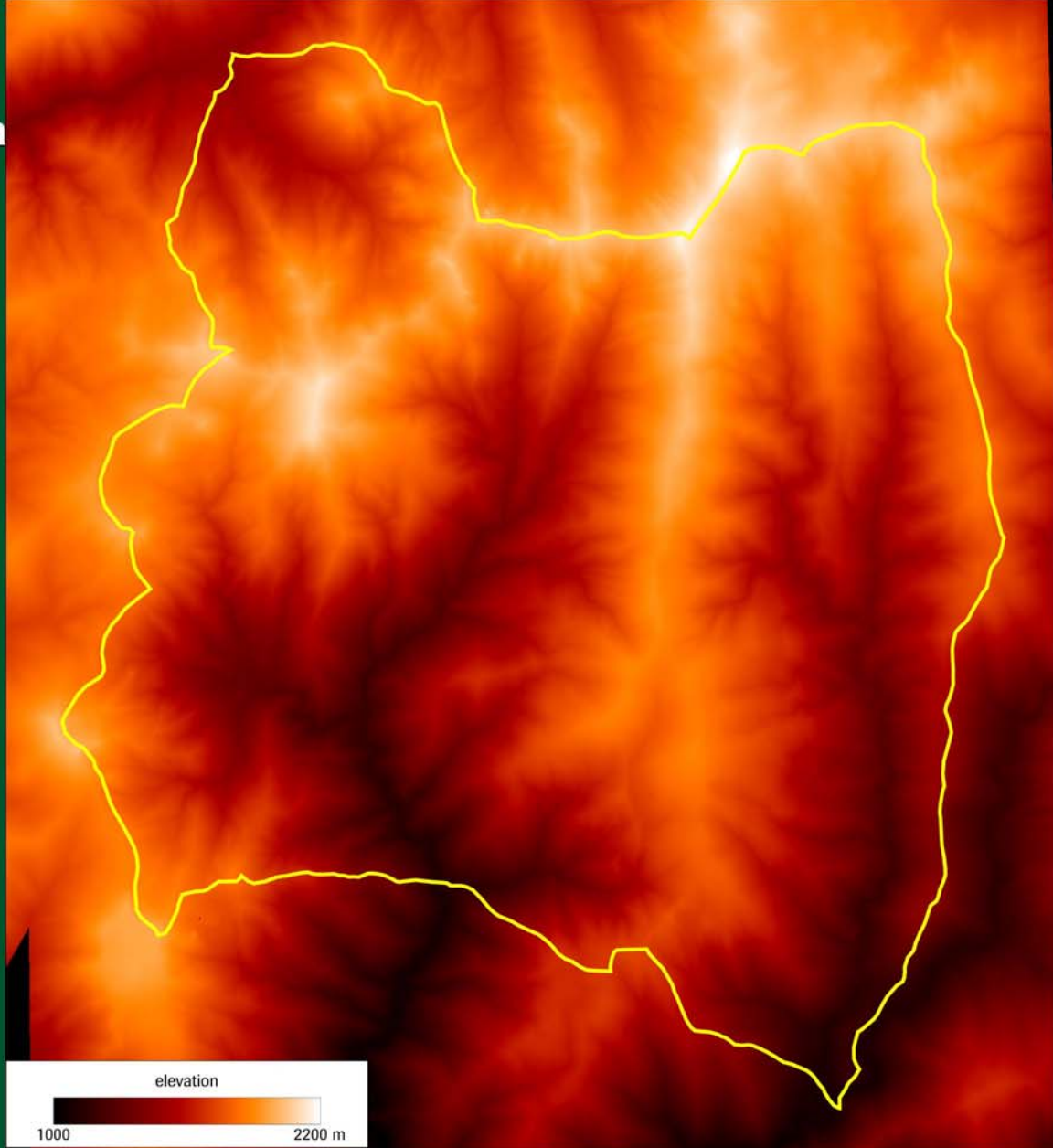


# LIDAR

## North Yuba Forest Carbon Area

### Elevation

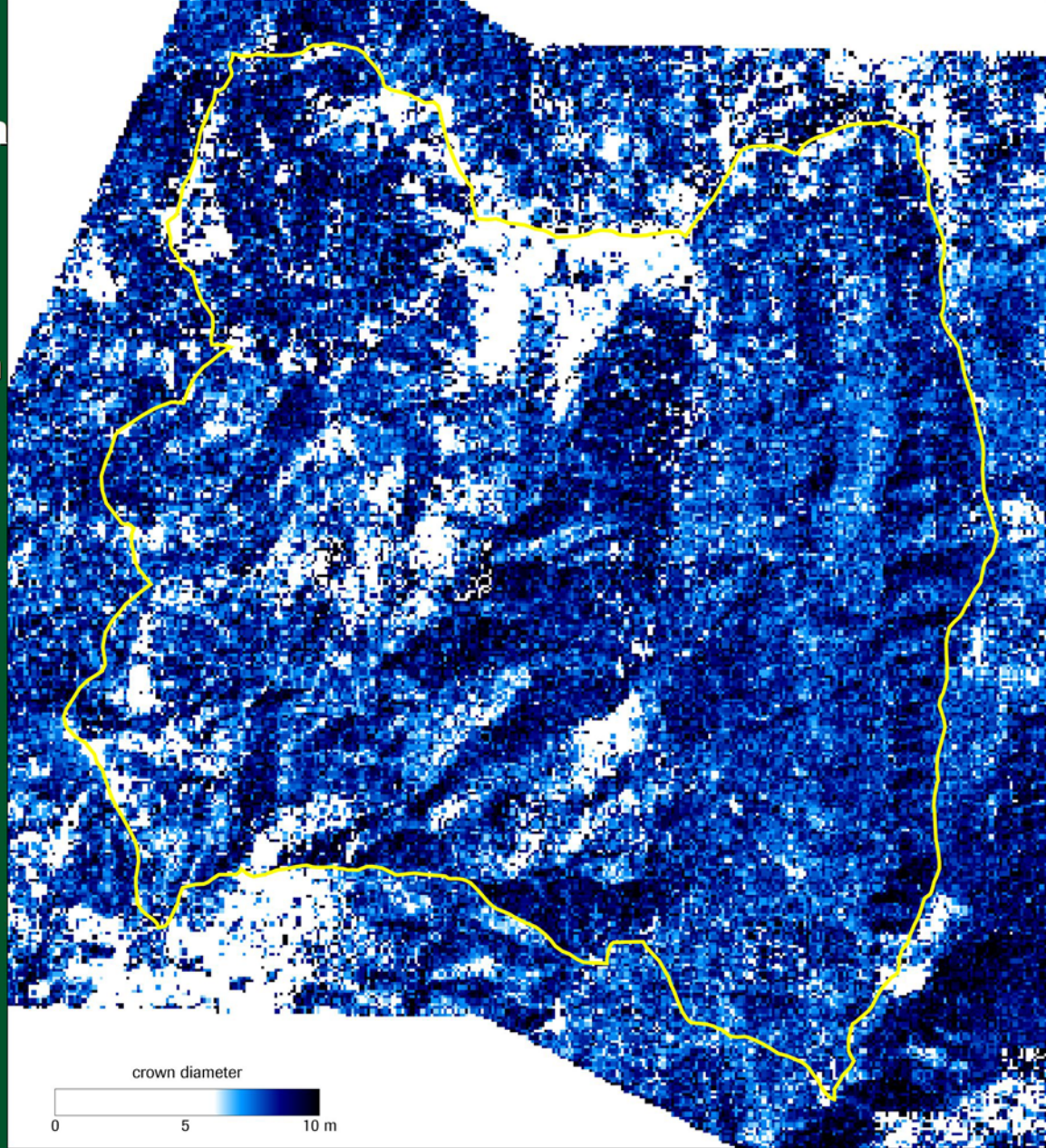
- Range 1000-2200 m



# QuickBird

## North Yuba Forest Carbon Area Crown Diameter

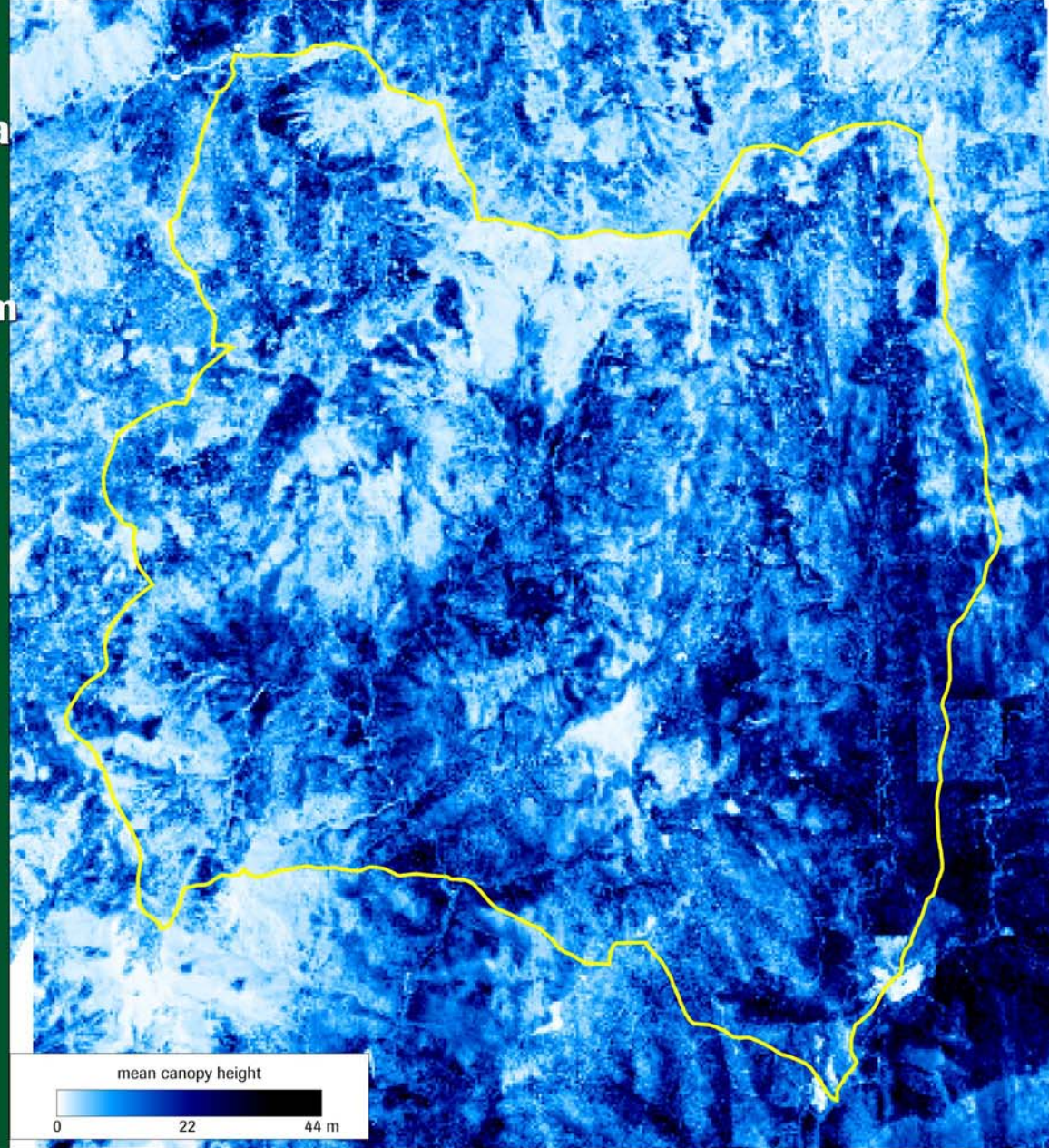
- Detection of 681 000 trees
- Average crown diameter =  $8 \pm 2$  m



# LIDAR

## North Yuba Forest Carbon Area Canopy Height

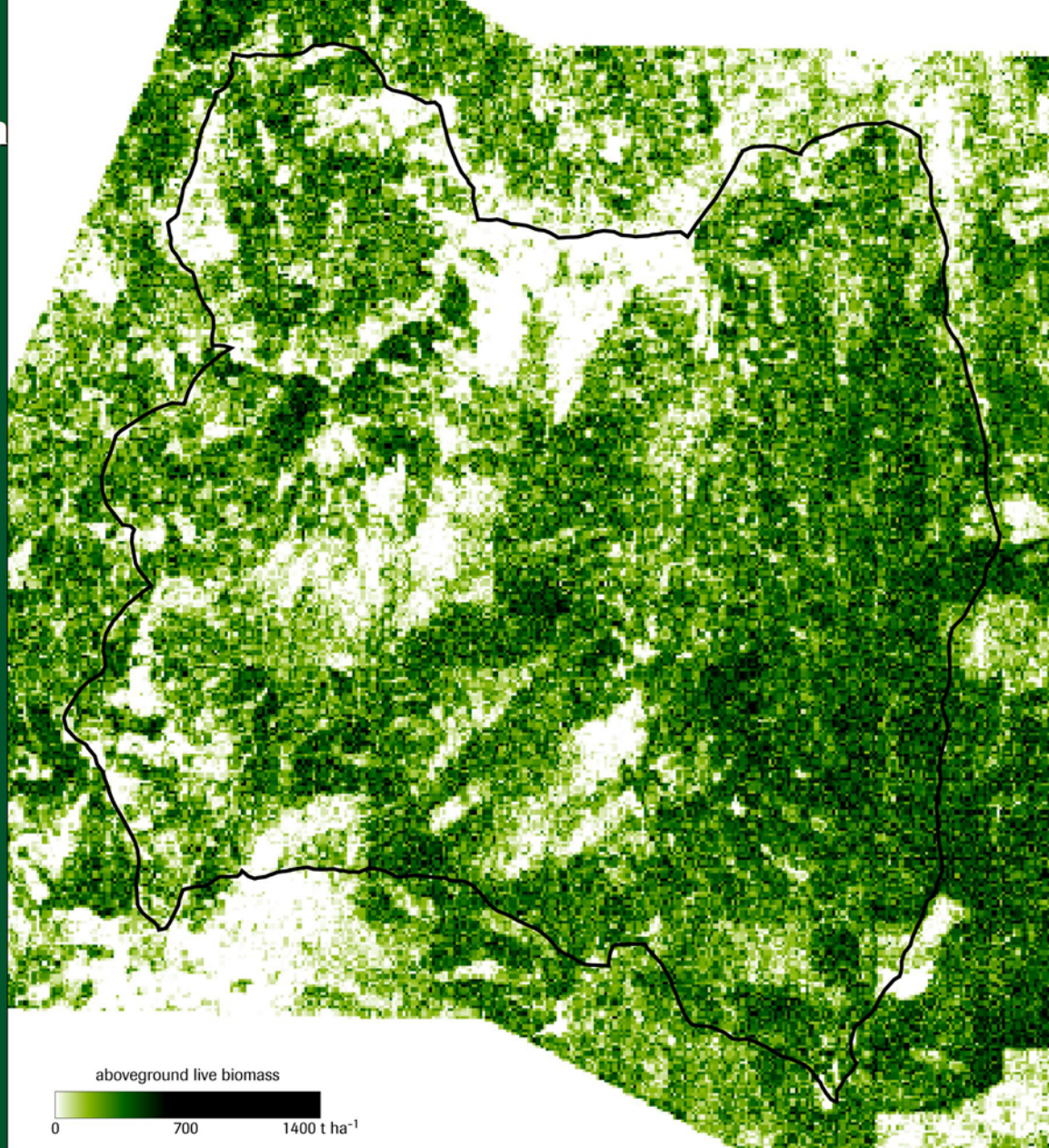
- Mean canopy height =  $34 \text{ m} \pm 15 \text{ m}$
- Quadratic mean canopy height  
 $12 \pm 7 \text{ m}$



# QuickBird

## North Yuba Forest Carbon Area Biomass

- Estimated average biomass  
 $240 \text{ t ha}^{-1} \pm 100 \text{ t ha}^{-1}$



# LIDAR

## North Yuba Forest Carbon Area Biomass

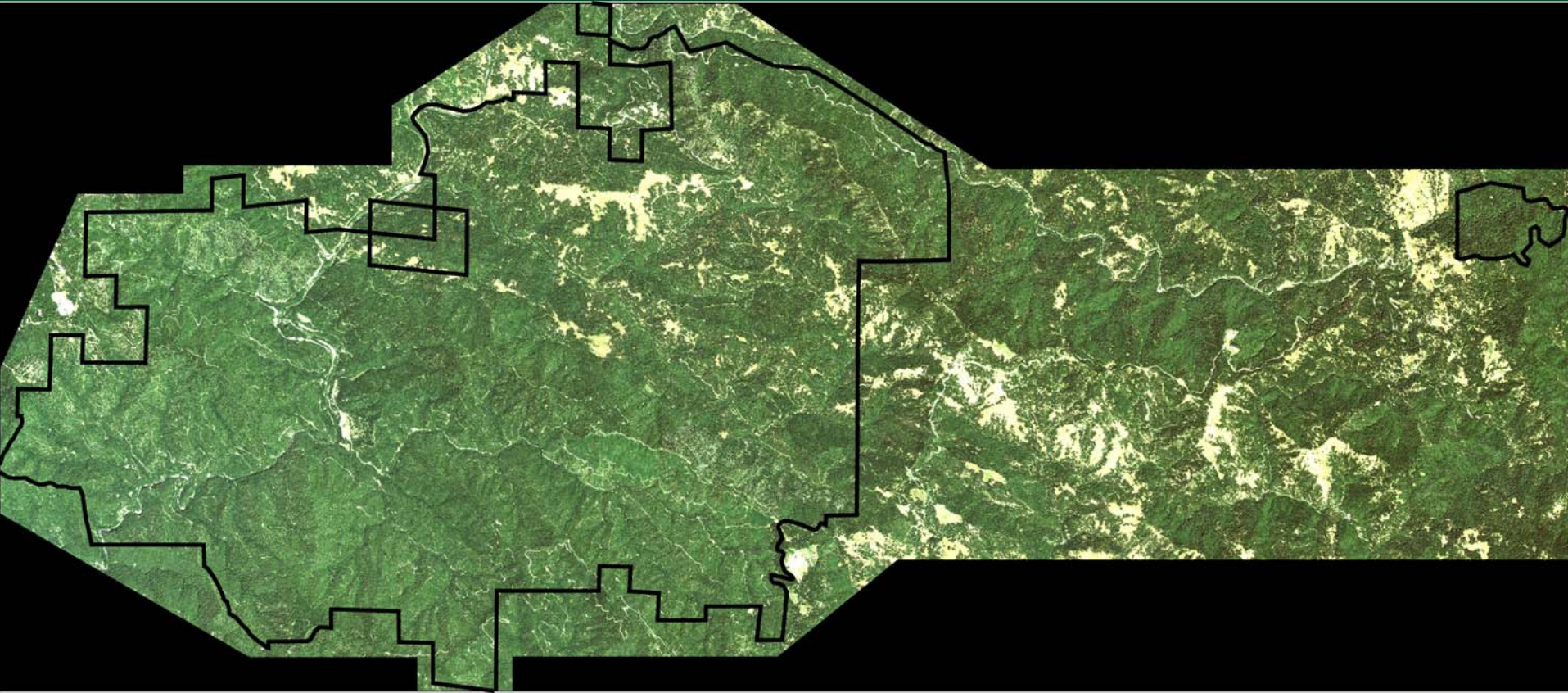
- Estimated average biomass  
 $320 \text{ t ha}^{-1} \pm 6 \text{ t ha}^{-1}$



# LIDAR

## Garcia-Mailliard

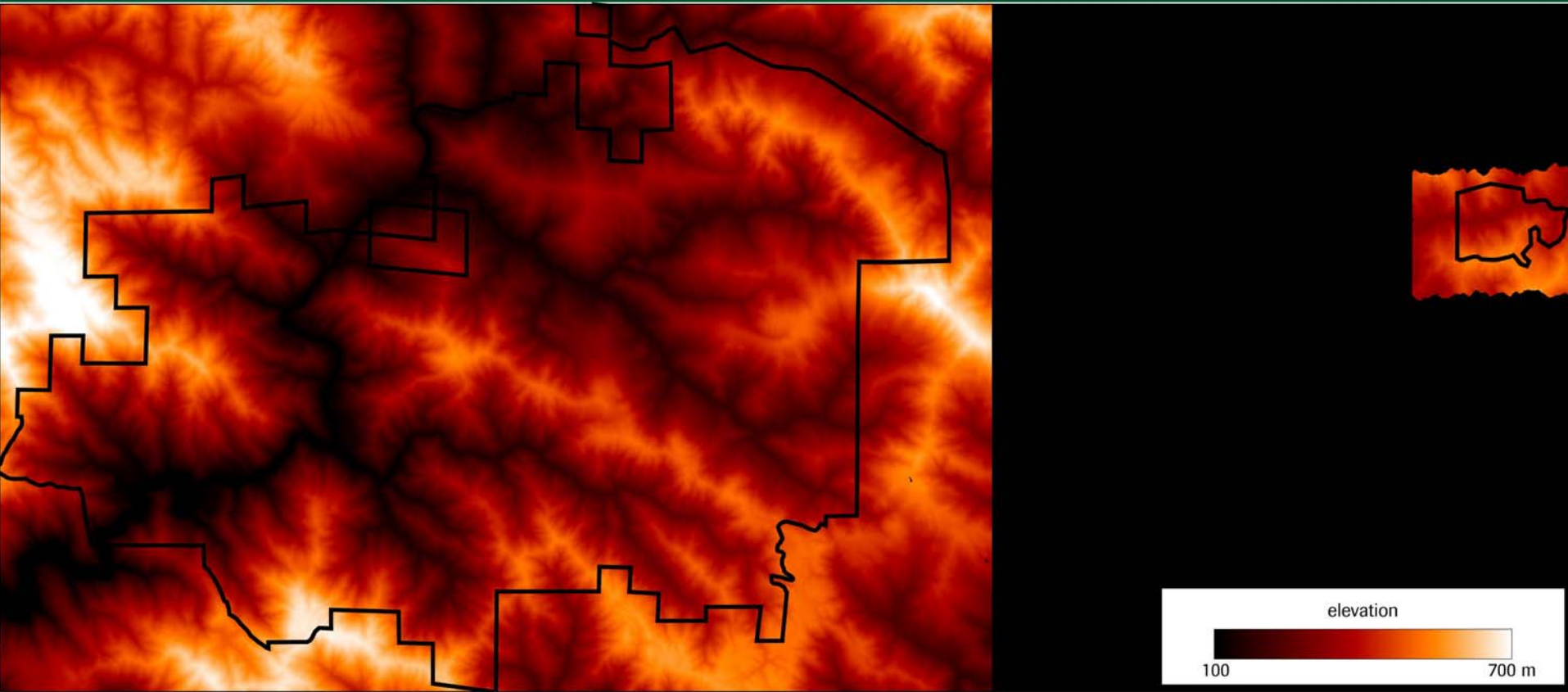
- Detected 1.7 million trees, average crown diameter  $8.2 \pm 4$  m
- Garcia biomass  $220 \pm 120$  t ha<sup>-1</sup>, Mailliard biomass  $260 \pm 160$  t ha<sup>-1</sup>



# LIDAR

Garcia-Mailliard

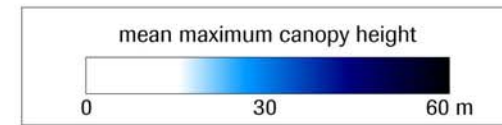
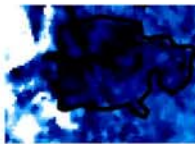
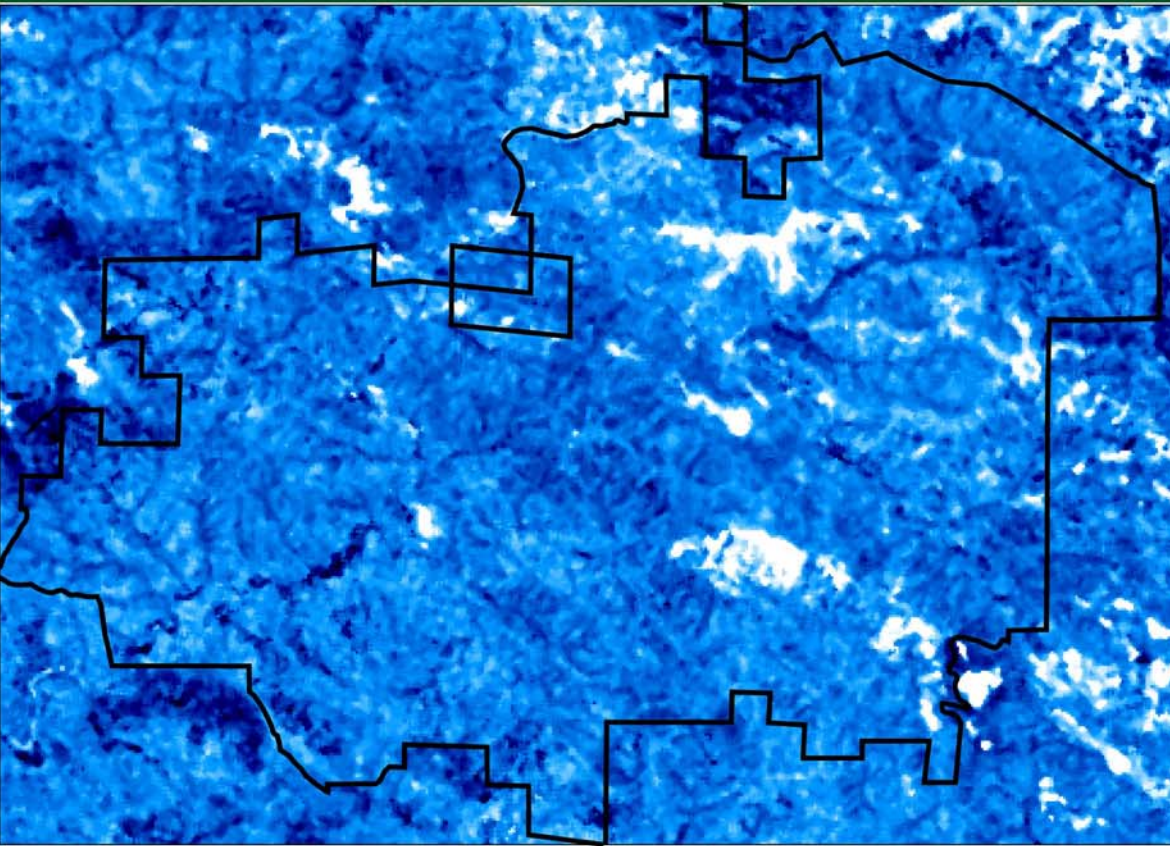
- Elevation range 100-700 m



# LIDAR

## Garcia-Mailliard

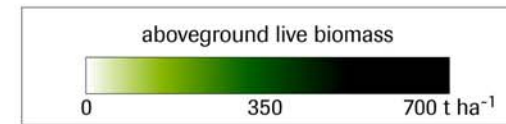
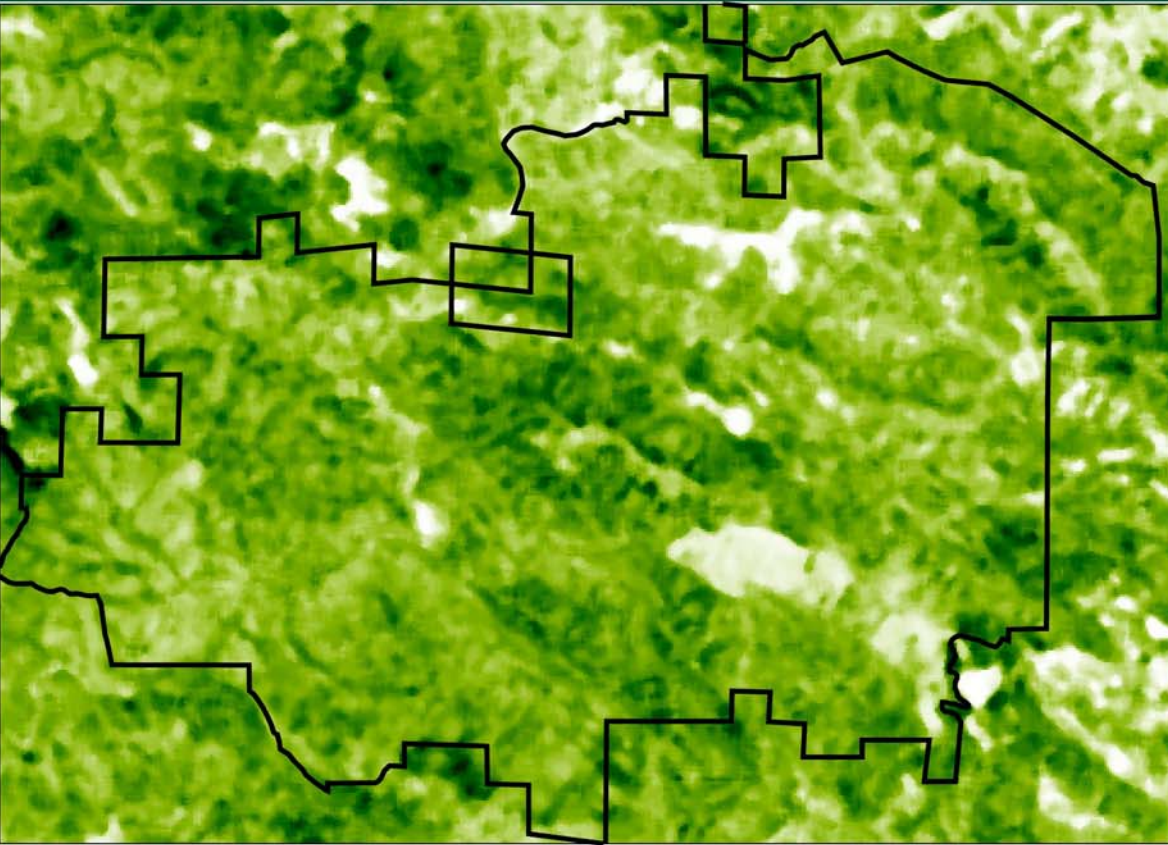
- Mean maximum canopy height  $32 \text{ m} \pm 11 \text{ m}$  (Garcia),  $58 \text{ m} \pm 16 \text{ m}$  (Mailliard)



# LIDAR

## Garcia-Mailliard

- Mean canopy height =  $34 \text{ m} \pm 15 \text{ m}$
- Quadratic mean canopy height  $12 \pm 7 \text{ m}$
- Estimated average biomass  $190 \text{ t ha}^{-1} \pm 4 \text{ t ha}^{-1}$



# Monitoring Forest Carbon in Sierra Nevada and North Coast Forests with Field Inventories, LIDAR, and QuickBird Satellite Images

## Presentation Outline

1. Forest Carbon Balance and Densities
2. Research Areas
  - a. North Yuba carbon
  - b. Garcia-Mailliard carbon
3. Methods
  1. Forest inventories
  2. LIDAR
  3. QuickBird
4. Results
5. Conclusions

# Monitoring Forest Carbon in Sierra Nevada and North Coast Forests with Field Inventories, LIDAR, and QuickBird Satellite Images

## Conclusions

1. Forest inventory is required to calibrate relationships of remote sensing-derived metrics and biomass
2. Two-step Monte Carlo analyses quantify the propagated error of combined measurement and statistical regression errors from forest inventories and LIDAR analyses
3. Shadows and bright spots in QuickBird images of tall temperate zone trees reduce the accuracy of automatic crown detection
4. LIDAR produces a smaller Monte Carlo-derived error of estimated biomass than QuickBird
5. Others can use the LIDAR-derived biomass regression equations to quantify forest carbon in adjacent forests of similar composition
6. Permanent plots and LIDAR data provide tools for monitoring and verification of forest carbon in the Garcia River forest for the California Climate Action Registry



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